

Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: An Australian perspective

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ABSTRACT

For many agricultural commodity sectors, efforts to meet international obligations regarding emissions reduction are increasing. The Australian cotton industry has already made advances in this regard and the high yields associated with Australian cotton production dramatically minimise greenhouse gas emissions intensity. However, certainty about the quantum of greenhouse gas emissions and the relative contribution of different components of the emissions profile is somewhat unclear; and opportunities for farm-level practice change have not been fully explored. The objectives of this paper were to, (a) build a robust greenhouse gas emissions profile for the product-chain of Australian cotton fibre (lint) grown in northwest New South Wales, (b) using Life Cycle Assessment (LCA), compare the relative contributions of the different industries involved in the product-chain of cotton fibre (e.g. fertiliser producers, cotton farmers, cotton ginning plants) and (c) assess the effects of an array of on-farm mitigation options. Testing the various management options provides information for growers and policy-makers about the relative emissions reduction benefits possible. Additionally, we compared results of previous Australian cotton production studies using similar assumptions and extrapolated the emissions profile to a national scale, with the intention of informing commodity and carbon markets.

The foreground data for the study were for the three production seasons from 2011–2012 to 2013–2014 in northwest New South Wales, with a functional unit of one tonne of cotton lint at port. We also drew upon published data, survey data, scientific literature and Australian and international databases. To ensure consistency between our approach and that applied to meet international emissions reporting obligations, we applied emissions formulae and factors from the Australian National Inventory Report, except where more specific published data were available. We assumed that 96% of production was from irrigated systems, with 85% of irrigation water pumped by diesel-powered irrigation pumps and a median irrigated yield of 10.3 bales per ha. We tested the sensitivity of the resulting emissions profile to a wide array of enterprise assumptions and calculation variables.

The climate change impact of cotton lint on a cradle-to-port basis was 1601 kg CO₂e per tonne of cotton lint. The ‘hot-spots’ within the emissions profile included the production and use of synthetic nitrogen (N) fertilisers (46% of emissions), the production and use of electricity and diesel used for irrigation (10%) and the production and use of diesel for farm machinery (9%).

Farm level management options with potential to minimise life cycle GHG emissions were: reducing N fertiliser rate from a commercial rate of 255 kg N/ha to 240 kg N/ha or 180 kg N/ha (2.6% and 13.2% emissions reduction); use of controlled-release and stabilised N fertilisers (5.9% reduction), changing from diesel to solar-powered irrigation pumps (8.1% reduction), changing from diesel to biofuel-powered farm machinery (3.4% reduction), changing from continuous cotton to a cotton-legume crop rotation (3.9% reduction) and use of N fertigation (2.1% reduction). Whilst we focused on farm-level mitigation strategies, these changes were placed in the context of the cradle-to-gate system, to account for associated changes in pre-farm and post-farm emissions.

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1. Introduction

Agricultural intensification and increased crop productivity from various farming systems is accelerating the pressure on agricultural resources (Kong et al., 2015). Cropping industries and government organisations are responding globally to pressure for sustainable resource use, as well as focusing on long-term productivity gains. The Australian Government's Emissions Reduction Fund is a typical example of such a response (DoEE, 2017) to the United Nations conference on climate change in Paris, which established targets in an attempt to limit global temperature increases (COP21, 2015).

The role of agriculture in reducing greenhouse gas (GHG) emissions and sequestering carbon is vital. Management options to reduce emissions are broad and include improved efficiencies of use of inputs such as fertiliser and diesel, greater use of renewable energy and modification of crop rotation systems. Opportunities to sequester carbon may also be available but were not included in the primary assessment of this paper due to uncertainties. The global potential for soil organic carbon (SOC) sequestration through improved crop management practices is 0.9 Pg C/year which may offset up to a third of the annual increase in atmospheric CO₂ estimated at 3.3 Pg C/year (Lal, 2004). In Australia, the potential to improve soil organic carbon in irrigated cotton-growing systems was reported in recent studies (Rochester, 2011; Hulugalle et al., 2014). Whilst emissions are inevitably associated with crop production, there are opportunities for food and fibre producers to participate in carbon-farming markets and secure environmentally-credentialed commodity markets that the potential to reduce atmospheric CO₂ levels.

Australian irrigated cotton production is highly profitable with gross margins that exceed those for grain and sugarcane farming. We chose cotton production for the present study because of the industry's significant contribution to Gross Domestic Product, its interest in environmental sustainability (Nachimuthu and Webb, 2016; Roth, 2014) and its capacity to respond to identified opportunities. Whilst we do not assess economic and environmental efficiency (as per Ullah et al., 2016), we do provide an example of brief economic analysis on yield and economic optimum nitrogen (N) fertiliser rate, and minimising tractor operations. The intentions were to (a) improve industry confidence about the likelihood of adoption and (b) benchmark sustainability indicators against conventional management practice. Even where economic and environmental outcomes do not currently coincide, it is critical to understand the environmental benefits of options that may be feasible (as is the focus of the present study) or may become more feasible as carbon and commodity market situations change. The Australian cotton industry is cognisant of growing international pressure for reduction in direct and indirect GHG emissions across all food and fibre commodities (Visser et al., 2015), and Australia's comparatively high yields dramatically minimise the GHG intensity or energy use intensity of its primary production industries compared to other global locations (Ullah et al., 2016; Kazemi et al., 2018).

Total cotton production in Australia varies annually and is directly related to water availability. The five year (2009–2014) average annual cotton production in Australia was 3.9 million bales from 334,775 ha to 96,074 ha of irrigated and dryland systems, respectively, with an annual gross value of \$2 billion (AU\$) (Roth, 2014). The industry helps to underpin more than 50 rural communities. Globally, Australia was the sixth largest cotton producer and the second largest cotton exporter by volume during the 2013–14 production season (Cotton Inc., 2018). Australian lint is typically of high quality and market value. Average lint yield in Australia is the highest in the world at 12 bales/ha (2.7 t/ha

(irrigated) in 2014–15 (Cotton Year Book, 2015) and 9.85 bales/ha (2.2 t/ha) (irrigated) in 2009–14 (Roth, 2014) due to breeding and crop management, including crop rotation, irrigation scheduling, pest management, crop nutrition and soil quality (Rochester and Constable, 2015).

Cotton is grown in the Australian states of Queensland (Qld) and New South Wales (NSW). In NSW, cotton is mainly grown in Namoi, Gwydir, Macintyre, Macquarie, Bourke, Tandou, Lachlan, Murrumbidgee and Murray Regions. The main cotton growing regions in Qld are Emerald, Biloela/Theodore, Darling Downs, Macintyre, St George and Dirranbandi Regions (Cotton Year Book, 2015). We chose to focus on the Namoi and Gwydir regions in northwest NSW, as production in this area is strongly representative of Australian cotton production (Hedayati, 2015).

Life Cycle Assessment (LCA) is a widely regarded and internationally-recognised method for quantifying the environmental impact of a production system, and is supported by ISO Standards for environmental management (ISO, 2006a, b). It enables mitigation strategies and unintended consequences of practice change to be explored, including 'spill-overs' into other parts of the production system (Hedayati et al., 2014). Whilst LCA can be applied across a broad array of impact categories, we limited this study to the climate change impact of cotton production on GHG emissions.

Given the significance of farm-level emissions from cotton production, we focused on this component of the supply chain. The presence of the myBMP best management program (myBMP, 2015; Roth, 2014), which forms a conduit for the adoption of the results, provides an additional reason for this focus. Approximately 45% of cotton growers participate voluntarily in the myBMP program (Cotton Australia, 2016) which is periodically updated to accommodate new research findings on soil health, soil carbon, water use, energy use and input efficiency. Given the diversity of cropping systems, even in quite homogenous agrarian systems, difficulties arise in establishing standardised enterprise assumptions and providing enterprise-specific recommendations which account for biophysical and economic trade-offs. We limited the scope of this study to providing information about emissions consequences and informing myBMP to allow individuals to make business decisions, rather than exploring trade-offs. However, we do provide foreground data, sensitivity analysis results and guidance about the relative merit of different management options from an environmental management perspective, thus providing a basis for economic feasibility to be weighed against likely environmental outcomes in the context of future carbon and commodity markets. Whilst the chosen management options differ in the level of investment required and their pay-back period, all have been adopted to some degree for other purposes or shown to be practically and/or economically feasible in some circumstances. Therefore, this paper provides guidance as to the likely environmental outcome of policy decisions surrounding options that might become incentivised. Options excluded on the basis of a lack of maturity and/or expected economic return are also discussed.

Despite existing studies about GHG emissions from soil, water and fertiliser management during cotton production in recent years (Macdonald et al., 2015; Schwenke and Kimber, 2015), published information about the whole-of-life cycle GHG emissions of Australian cotton production is limited. Existing studies include: a cradle-to-gate study encompassing skip-row planting in Qld; a study in the context of carbon pricing (Maraseni et al., 2010); a practical calculator to support participation in the Emissions Reduction Fund (Visser et al., 2015; DoEE, 2017); inventory data to underpin broader studies (AusLCI); and farm-specific and regionally-applicable approaches (Tan et al., 2013).

Information gaps about the emissions intensity of Australian

cotton production and the relative contribution of different components of the emissions profile are evident, especially when viewed from a whole-of-life cycle perspective. The aim of this paper is to better inform policy makers who may wish to incentivise management options, to support industry participation in both carbon and secure commodity markets, and to support growers in practice change. To achieve this aim we assessed the relative effect of a broad array of farm-level emissions reduction strategies, conducted sensitivity testing, compared results to those of other studies on the basis of like assumptions, and extrapolated the emissions profile to a national perspective. At a farm level, we specifically tested the hypotheses that the following strategies would lead to a reduction in life cycle GHG emissions:

1. Reducing the fertiliser N rate from the average commercial rate;
2. Using controlled release and slow release N fertiliser products;
3. Replacing diesel-powered with solar-powered irrigation pumps;
4. Replacing diesel with biofuel to power farm machinery;
5. Replacing continuous cotton with a cotton-legume crop rotations;
6. Applying N fertiliser by fertigation.

This study provides a baseline from which the effect of practice and technological changes (and predicted potential changes) to the industry over time could be quantified.

2. Methods

2.1. Goal and scope

We applied the LCA method to calculate the GHG emissions profile of cotton production and associated GHG mitigation strategies. The scope of the environmental assessment was limited to climate change impact. The functional unit of the LCA study was one metric tonne cotton fibre (lint) produced in a continuous cotton production system and delivered for export at port. The geographical scope of the LCA was the cotton growing region of northwest NSW Australia, in the Namoi-Gwydir regions including the towns of Narrabri, Moree and Walgett. The temporal scope of the LCA was the three cotton production seasons of 2011–2012, 2012–2013, and 2013–2014.

2.2. System boundary

The system boundary of the LCA study (Fig. 1) included the pre-farm stage (i.e. production and transport of raw materials), the on-farm stage (i.e. cotton farming practices) and the post-farm stage (i.e. cotton ginning and the transport of cotton lint to an export port). This approach provided an understanding of the full life cycle consequences of pre-farm, on-farm and post-farm practice changes.

2.3. System assumptions

We assumed the following attributes for cotton production in northwest New South Wales, which also apply to a typical Australian cotton production system. Cotton is an annual summer crop, with a 6-month production season. Production starts with soil preparation including: bed forming, weed removal, fertiliser application and irrigation (if required), with planting in October–November. Nitrogen fertilisers are applied from June–August, with top-dressing (as broadcast or water-run N fertiliser) and application of plant protection products (e.g. pesticides) during the growing phase from November–February. Defoliation of matured

cotton occurs between the last week of March to mid-April, with harvest using mechanical picker between April–May. Mulching of cotton stubble, root cutting and pupae busting occur sequentially in the month after harvest. At the time of this study, half of the cotton production systems were back-to-back cotton at least two continuous cotton crop over two years (Roth Rural, 2013), and the other half included a break crop. Therefore, we compared a continuous (back-to-back) system with a cotton-break crop system. After picking, cotton is trucked off-farm to the gin where lint, cottonseed and trash are separated. Generally, the process involves cotton drying, removal of leaf trash and dirt, separation of lint and seed, then pressing into bales.

Both dryland and irrigated cotton production occurs in the region with a dominance of irrigated cotton production (96% of total volume of cotton production in 2014–15), although the proportion that is irrigated varies yearly depending on water availability and rainfall. The percentage of irrigation water sourced from surface water (80%) versus groundwater (20%) assumed for this study is based on the percentage reported for extractive agricultural use in NSW in 2012–2013 (ABS, 2014). We assumed that 85% of the irrigation water was pumped by diesel-powered irrigation pumps and 15% by electric pumps (Foley et al., 2015). The total dynamic heads for water pumped from surface water and groundwater were assumed to be 8 m (Welke, 2011) and 35 m (NSW Water, 2009a; b), respectively.

We applied the relative contributions of cotton lint (42%), cottonseed (49%) and gin trash (9%) for a typical Australian ginning plant (RIRDC, 2014). Clean cotton fibre bale weight was 227 kg and median farm yield was 10.28 bales per ha. All key system assumptions described above were challenged through sensitivity testing. All process flows with a cumulative mass or energy of less than 1% were excluded, e.g. packaging glues used at the cotton gin.

When assessing mitigation options, the N fertiliser application rate was modified from a commercial rate of 255 kg N/ha to 240 kg N/ha, the rate at which lint yield is reported to be maximised (Macdonald et al., 2015), and also to 180 kg N/ha, the economically optimum rate according to Visser et al. (2015). The controlled-release (polymer-coated urea) and stabilised fertilisers (urea treated with a nitrification inhibitor) were included in the analysis. We applied a 52% reduction in each emissions factor during the on-farm phase, as per Tian et al. (2015). The increase in fertiliser manufacturing emissions required to produce these products was negligible and below the 1% cut-off for inclusion in the LCA. The use of fertigation as a mitigation strategy was assessed by removing the pre-plant fertiliser operation and reducing the N₂O produced from applied N by 80% (Antille, 2018).

Chickpea was modelled as a surrogate representing a typical legume crop grown in rotation with cotton, given the ready availability of data on emissions from chickpea production specific to northwest NSW. The alternative rotation was one annual chickpea crop followed by three annual cotton crops. For the purpose of this study, we did not credit the cotton with the N fixed during growth of the chickpea crop, instead applying a yield increase to account for break-crop effects. Whilst some cotton farmers reduce the N fertiliser application rate for cotton grown after legumes, those that do so are in the minority, with 180–240 kg N/ha still commonly applied. Also, we did not debit the system with the foregone carbon sequestration that occurs during legume production due to the lower biomass of legume crops (Brock et al., 2016a, b) as there is still uncertainty about the extent of trade-off between carbon sequestration and N fixation in the present system. Further investigation of the role of legumes in rotation is required. In order to achieve this, it is necessary to better understand the relative degree of substitution by growers between synthetic and biological N sources and the extent to which the carbon cost of N fixation has a

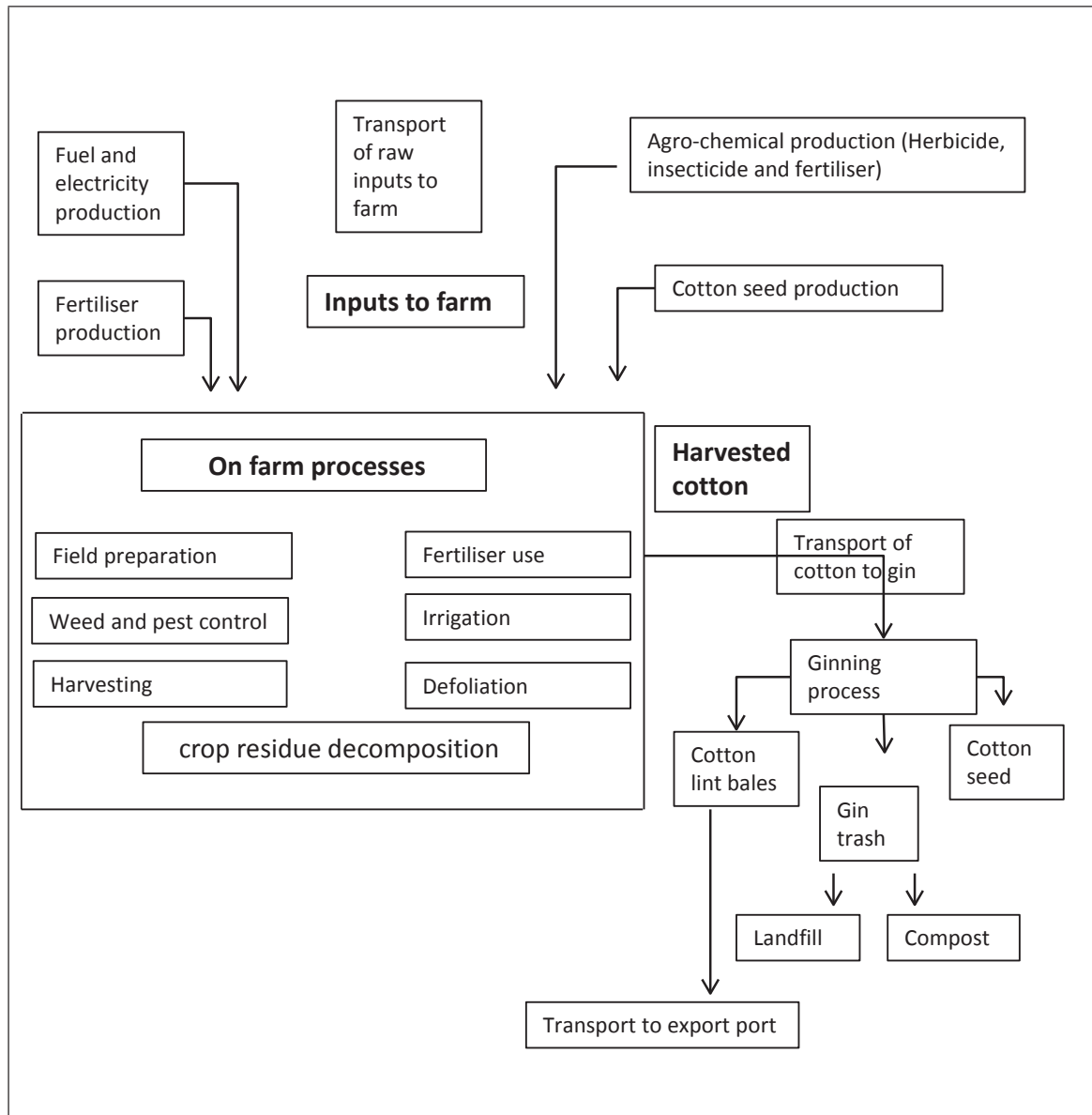


Fig. 1. System boundary for the primary LCA.

role to play, an issue which has been uncovered but is not yet represented in IPCC calculation methods (Brock et al., 2016a, b).

For solar-powered irrigation pumps, 3 kW solar panels were assumed as the power source. For biofuel-powered farm machinery, biodiesel was assumed to be produced as methyl ester from rapeseed, with the CO₂ emissions from the combustion of biodiesel considered biogenic and thus not included in the impact assessment. Also, we discussed rather than analysed the full life cycle consequences, including alternative uses of the biomass and displacement of other land uses, providing an upper estimate of total life cycle emissions savings. We also accounted for differences in density and energy intensity of diesel and biodiesel.

2.4. Data sources

The study drew on published data, survey data, scientific literature, and Australian and international databases. Background data, such as those about fertiliser and diesel manufacture, diesel combustion and manufacture of plant protection products, were

obtained from the Australian Life Cycle Inventory (AusLCI) database (ALCAS, 2013; RIRDC, 2014) and international databases (e.g. Ecoinvent), modified for Australian conditions. Data about plant production products (herbicides, insecticides and growth regulators) were grouped and then modelled as three major inputs.

Foreground data (Table 1) associated with system inputs, practices and yields were obtained from journal papers, questionnaires sent to cotton farmers, gross margins, industry surveys, case-study research and the Australian Bureau of Statistics (ABS, 2014). Expert opinion from industry representatives was obtained to validate pre-farm data. Representatives from two ginning plants located in northwest NSW were interviewed to obtain data about the post-farm stage. The economic analysis data was based on Powell and Scott (2011). We applied the most representative, rather than average yield data.

2.5. Modelling approach

We used SimaPro 8.0.3 software (Pré Consultants, 2008) to

Table 1
Foreground life cycle inventory data.

Inputs/outputs	Quantity	Inputs/outputs	Quantity
Farm outputs per hectare		Cotton-ginning inputs per hectare	
Cotton lint (kg)	2383.5	Liquefied petroleum gas (litre)	22.0
Cottonseed (kg)	2788.7	Electricity (kWh)	351.7
Cotton residues (kg)	9827.1		
Farm inputs per hectare		Gin trash treatment	
Seeds for planting (kg)	13.0	Gin trash sent to landfill (kg)	127.8
Irrigation water (mega litre)	7.7	Gin trash stockpiled for composting (kg)	383.2
Diesel for machinery (litre)	122.1	Life cycle transport-distance	
Diesel for irrigation (litre)	99.5	Road transport of farm inputs to farm (km)	500.0
Electricity for irrigation (kWh)	58.5	Road transport of cotton crop to gin (km)	35.0
Urea (kg)	315.0	Rail transport of cotton lint to port (km)	550.0
Anhydrous ammonia (kg)	120.0	Road transport of gin trash to landfill (km)	30.0
Mono ammonium phosphate or MAP (kg)	113.0		
Herbicides (kg)	6.6		
Growth regulator (kg)	1.59		
Insecticides (kg)	0.83		
Polyurethane packaging plastic (kg)	10.5		

conduct the LCAs, with calculations based on the methodologies presented in the 2013 National Inventory Report (NIR) (Australian Government, 2015). We then applied the Australian Impact Method, Australian Indicator Set V3 (ALCAS, 2013). The global warming potentials (GWPs) applied for CO₂, N₂O, and CH₄ were 1, 298, and 25, respectively (Australian Government, 2015a). As the NIR methods do not include CH₄ emissions on-farm, CH₄ is only reported as a component of pre-farm processes, where it is expressed in CO₂-equivalents (CO₂e). For consistency with these guidelines, we excluded CO₂ absorbed by the cotton crop during its growth and the CO₂ released from the decomposition of cotton residues in the field (i.e. biogenic CO₂) from the primary LCA. We challenged this assumption during sensitivity testing. We also assumed that background levels of soil organic N had reached a steady state. Calculated N₂O emissions were mainly based on the methods and calculation factors provided in the NIR, except where more specific published data were available. We drew data from an Australian cotton-related publication (Australian Government, 2015b) when calculating fertiliser-related emissions and accessed data from Muhammad (2011) when calculating emissions from the decomposition of cotton residues.

2.6. Sensitivity testing

The robustness of the calculated emissions was challenged through sensitivity analysis for key input data and model assumptions. Three variables were chosen for sensitivity testing because of their importance in achieving sound extrapolation of the present study to a national level and two variables were chosen due to their bearing at both a farm level and for extrapolation.

The primary LCA was prepared for irrigated cotton production, with emissions from dryland production calculated separately and used to replace 4% of the primary LCA. We present emissions results for both systems separately and discuss the impact of a change in the proportion of these systems, subject to the relative availability of irrigation water and soil moisture. Whilst it is hypothetically possible that a change in proportion might be used as a mitigation strategy at a farm level, the primary intent is to test the effect of the assumed proportion on regional and national emissions. The second key variable tested was the N₂O emission value, with the effect of applying national and regional values compared (Hedayati et al., 2015a). The representativeness of the region under study provided the third test, providing clarity about the extent to which the present study can be extrapolated nationally. This test also provided an indication of the potential change in calculated emissions if practices and climate were to become more representative of

southern or more northern systems in the future. Whilst the industry as a whole may move spatially, the intention is again to test the effect of this assumption, rather than present this as a mitigation strategy. As a further step, we adjusted the results of several previous studies (e.g. Visser et al., 2015; Maraseni et al., 2010; Tan et al., 2013; ALCAS, 2013) to a common system boundary and allocation method, and then compared our results with these other studies.

Whilst biogenic carbon was excluded from the primary LCA on the basis of consistency with the IPCC (IPCC, 2006) and NIR, we also questioned the sensitivity of the emissions profile to this assumption. Even though biogenic carbon is deemed to be part of a natural balanced cycle, considerable opportunity exists to modify residue management. So, this variable may provide both a test of the robustness of the present study and also constitute an emerging mitigation option. As a final test, we considered the sensitivity of the emissions profile to an array of individual inventory parameters. This provides clarity about the effect of the chosen value for each parameter. Also, by presenting the foreground data, assumptions can be modified for future regional studies and accommodate the unique nature of each farm-level enterprise, for which a percentage change in a single attribute can be applied. Even though there would likely be interactions between some parameters, we tested the implications individually.

2.7. Treatment of co-products

As cotton systems produce multiple products, it is necessary to partition the climate change impact between co-products to understand the impacts of lint production. The partitioning was guided by a hierarchical procedure in ISO 14044:2006 (ISO, 2006b). Given the difficulties and uncertainties associated with providing robust subdivision of processes or system expansion, we considered economic allocation as the most appropriate means of partitioning, despite the dynamic nature of commodity prices. We applied an average cotton lint price from 2011 to 2014 of \$2070/t (\$470/bale) and average cottonseed price of \$300/t, allocating approximately 86% of the life cycle climate change impact to lint. Whilst allocation based on per unit mass is possible, this shifted the majority of the impact to the cottonseed, whereas the primary product of interest is lint.

As a means of testing the effect of choosing economic allocation, we further explored system expansion (Hedayati et al., 2015b), consulting experts involved in animal feed production and oilseed supply. As uncertainty remained about the marginal displaced product associated with a marginal increase in lint production, we

considered an array of potential substitutes for cottonseed on the basis of metabolisable energy, crude protein and oil content. Emissions from these substitutes were subtracted, with the remaining emissions allocated to the lint. The exact proportion of the total produced cottonseed in northwest NSW used as animal feed was unknown. However, in Central Qld, 90% of total cottonseed produced is used as animal feed and the remainder crushed to extract cottonseed oil (QLD DAFF, 2013). Cargill Australia (Narrabri) crushes approximately 80% of the total cottonseed produced in the region. So, we applied a fraction of 20% of cottonseed as animal feed and then conducted sensitivity testing to determine the effect of this assumption.

3. Results

3.1. Emissions profile

Based on the economic allocation approach, the calculated life cycle GHG emissions for 1 t mixed irrigated and dryland cotton at port was 1601 kg CO₂e. The GHG emissions from the pre-farm stage, on-farm stage and the post-farm stages were 406 kg CO₂e, 776 kg CO₂e and 419 kg CO₂e, respectively (Table 2). The proportion of lint and seed affected the calculated emissions intensity, with sensitivity testing during economic allocation revealing that changing lint/seed proportions led to a climate change impact of 14.6%. This change, along with the impact of a change in cottonseed price (12.3%) and lint price (5.1%) were not considered substantial in comparison to the changes in calculated emissions in other natural fibre production LCAs where economic allocation has been applied (Brock et al., 2013). The emissions hot-spots, which informed the choice of mitigation strategies, included the production and use of synthetic N fertilisers (46% of emissions), the production and use of electricity and diesel for irrigation (10%) and the production and use of diesel for farm machinery (9%) (Fig. 2). Most diesel-related emissions were due to combustion on-farm (83%), with the remainder occurring pre-farm.

The production and use of synthetic N fertilisers contributed 705 kg CO₂e/t lint, with fertiliser production contributing approximately 17% and fertiliser use contributing 28% of the total life cycle GHG emissions. For the use stage, 80% of emissions were made up

of direct N₂O emissions (nitrification and denitrification), and indirect N₂O emissions (volatilised ammonia, nitrate leaching and nitrate runoff) (IPCC, 2006). Approximately 20% of the use-stage emissions were CO₂ emissions from the hydrolysis of urea in the field.

3.2. Application of the system expansion approach

When a system expansion approach was applied, calculated emissions from lint production were lower (Hedayati et al., 2015a, Table 3). Cottonseed creates a larger environmental burden based on its protein, energy and oil characteristics, compared to that based on economic value.

3.3. Comparison with previous Australian cotton LCA studies

Our calculated climate change impact on a cradle-to-port basis of 1601 kg CO₂e/t lint is consistent with several previous studies (Table 4). Once adjusted for a common system boundary and allocation method, the cited studies had an average emissions intensity of approximately 1150 kg CO₂e (RIRDC, 2014; Khabbaz, 2010; Tan et al., 2013). In addition to specific dryland and irrigated system case-studies, the study by Tan et al. (2013) includes a regionally-applicable dataset, with adjusted emissions of 1531 kg CO₂e/t lint. Two further studies, once adjusted, gave emissions of approximately 1450 kg CO₂e/t lint (Visser et al., 2015; Cotton Inc. and PE International AG, 2012). The adjusted emissions for AusLCI (ALCAS, 2013) were 1760 kg CO₂e/t lint. Maraseni et al. (2010) reported higher emissions for both dryland and irrigated production, but this was because they applied the higher IPCC N₂O emission factors due to the carbon pricing policy focus of their work, creating a discrepancy which was also reported by Roelandt et al. (2005). The lower Australian emissions factor for cotton is based on extensive field measurement (Grace et al., 2016).

3.4. Evaluation of GHG emissions mitigation strategies and gross margin variation

The effect of an array of mitigation strategies and gross margin variations for selected mitigation strategies is presented in Table 5.

Table 2
Process-specific climate change impact for cotton lint.

Process	Climate change impact (kg CO ₂ e/t lint)
Pre-farm stage	
Production of synthetic fertiliser	267.7
Production of herbicides, insecticides, and growth regulator	55.3
Production of diesel	42.1
Production of electricity	23.4
Production of aviation fuel	1.6
Transport of raw materials to farm (500 km distance)	15.8
Total for the pre-farm stage	405.9
On-farm stage	
Farm machinery	125.5
Irrigation	108.0
Decomposition of cotton residues in the field	75.3
Use of fertilisers	442.0
Transport of seed cotton from farm to gin	24.8
Total for the on-farm stage	775.6
Post-farm stage	
Seed cottonseed drying (LPG-powered process)	190.6
Gin machinery (electricity-powered operation)	148.0
Bale packaging	16.6
Gin trash treatment	41.8
Cotton lint rail transport to port (550 km distance)	22.2
Total for the post-farm stage	419.2
Whole life cycle	
Total for the life cycle (cradle-to-port)	1600.6

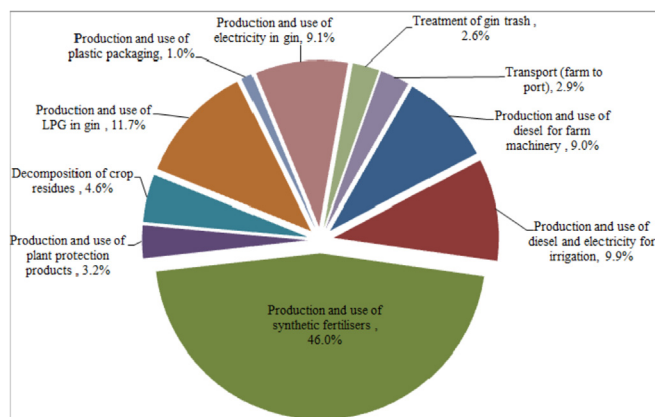


Fig. 2. GHG emission profile for cotton lint at port.

3.5. Sensitivity testing

3.5.1. Change in proportion of irrigated versus dryland cotton

The results of the sensitivity test in which the cotton production system was changed to a solely dryland and then solely irrigated system are presented in Table 6.

Whilst the inter-annual shift between system types is not extreme and there is a sound basis for the proportional split chosen for the present study, the results presented here provide a basis for adjusting calculated emissions as the proportion changes over

time, rather than as a farm-level mitigation strategy. Even though emissions intensity was lower for dryland production, a lower yield only partly offset lower input emissions.

3.5.2. Change in fertiliser-related N_2O emission values

The calculated climate change impact for the primary LCA was moderately sensitive to the chosen fertiliser-related N_2O emission factors (Table 7). This was because the regional emission factors partly were used to develop the national cotton emission factors, thus the results were not independent of one another.

3.5.3. Change in location of the study area

When the key inventory data for the northwest NSW cotton production system were replaced with the corresponding inventory data for systems in other regions, the calculated emissions intensity varied by less than 10%, except for Central Qld where the calculated emissions intensity was 23% higher (Fig. 3) primarily due to lower yields. Different modelling parameters, including N_2O emissions factors, ranging from 0.0033 for the Darling Downs to 0.0105 for Southern Queensland, were applied for each region (Table 8). This provides confidence in the assumptions applied and results generated for the present study. The lack of variability also assists with extrapolation to a national level.

3.5.4. Change in assumptions about biogenic carbon dioxide

When we tested the sensitivity of the primary LCA to the inclusion of biogenic CO_2 we found the calculated emissions decreased to a net sequestration of 2360 kg CO_2e per tonne of lint.

Table 3
Climate change impact of the functional unit under different system expansion scenarios.

System expansion scenario	Animal feed systems		Seed oil systems		Climate change impact (kg CO_2e /t lint)
	Product displaced by cottonseed	Product balancing CP and ME	Product displaced by cottonseed	Products balancing OC, CP, and ME*	
Scenario 1	Wheat	Sorghum	Canola seed	Sorghum and lupins	1254
Scenario 2	Wheat	Lupins	Canola seed	Sorghum and lupins	1306
Scenario 3	Barley	Sorghum	Canola seed	Sorghum and lupins	1279
Scenario 4	Barley	Lupins	Canola seed	Sorghum and lupins	1307

*OC = oil content, CP = crude protein, ME = metabolisable energy.

Table 4
Comparison between the climate change impacts reported in other studies and the adjusted impact calculated in this study.

Study	Initial system boundary	Initial functional unit	Climate change impact	
			As Reported	Adjusted (kg CO_2e /t lint)
This study	Cradle to port	1 t lint at port	1601 (kg CO_2e /t lint)	
AusLCI (ALCAS, 2013)	Cradle to gin bale press	1 t lint at gin	1695 (kg CO_2e /t lint)	1760 ^a
(RIRDC, 2014) (for Australia)	Cradle to gin bale press	1 t lint at gin	1164 (kg CO_2e /t lint)	1187
Cotton Inc. and P.E. International A.G. (2012) (for Australia)	Cradle to gin bale press	1 t cotton lint produced at gin in Australia	1163 ^c (kg CO_2e /t lint)	1440 ^d
Visser et al. (2015) (Darling Downs)	Cradle to gin bale press	1 bale of cotton lint	323 (kg CO_2e /bale)	1446
Tan et al. (2013) (average of dryland and irrigated case studies for the Namoi Valley)	Cradle to farm gate	1 t of seed cotton produced at farm	345 (kg CO_2e /t seed cotton)	1129
Tan et al. (2013) (regionally-applicable study for the Namoi Valley)	Cradle to farm gate	1 t of seed cotton produced at farm	468 (kg CO_2e /t seed cotton)	1532
Khabbaz (2010) (for Australia)	Cradle to port	1 ha of cotton land	2860 (kg CO_2e /ha)	1163
Maraseni et al. (2010) (for case studies in Darling Downs)	Cradle to farm gate	1 t of irrigated cotton lint	2674 (kg CO_2e /t lint)	3088 ^b
Maraseni et al. (2010) (for case studies in Darling Downs)	Cradle to farm gate	1 t of dryland cotton lint	1590 (kg CO_2e /t lint)	2004 ^b

^a In AusLCI, the total GHG emissions per ha of cotton was divided by the collective mass of lint + seed + gin trash; whereas in the present study, the total GHG emissions per ha was divided by the collective mass of lint + seed. If the mass of gin trash in AusLCI was excluded, the climate change impact would be ~1890 kg CO_2e /t lint.

^b Maraseni et al. (2010) applied the IPCC default N_2O emissions factor of 0.0125.

^c Australia was not included.

^d Generated for Australia.

Table 5

Reduction in emissions intensity and improvement in gross margin for cotton lint production due to the implementation of mitigation strategies.

Mitigation strategy	Process stages affected	Total emissions (kg CO ₂ e)	% reduction in emissions intensity	Gross margin/ha (AU\$)	Emissions per unit of gross margin (CO ₂ e/AU\$)
Yield-optimised N rate (240 kg N/ha)	Production, transport and use	1560	2.6%	1744	1.12
Economically-optimised N rate (180 kg N/ha)	Production, transport and use	1390	13.2%	1795	1.29
Use of controlled-release and stabilised N fertilisers	Use	1507	5.9%		
Fertigation, water-run urea (tractor operation subtracted)	Pre- and on-farm diesel-production and combustion	1567	2.1%	1734	1.11
Legume crop rotations	Break crop effect on yield	1539	3.9%		
Solar-powered irrigation pumps	Energy manufacture, use and transport to farm	1470	8.1%		
Biofuel-powered farm machinery	Energy manufacture, use and transport to farm	1546	3.4%		

Table 6

Results of the sensitivity analysis—changing the cotton production system to solely dryland or irrigated cotton.

Process	Climate change impact (kg CO ₂ e/t lint)		
	This study	Irrigated	Dryland
Pre-farm stage			
Production of synthetic fertiliser	267.7	276.0	159.0
Production of herbicides, insecticides, and growth regulator	55.3	51.9	109.0
Production of diesel	42.1	42.5	43.7
Production of electricity	23.4	24.9	0.0
Production of aviation fuel	1.63	1.74	3.6
Transport of raw materials to farm (500 km)	15.8	15.2	10.7
Total for the pre-farm stage	406.9	412.2	322.0
On-farm stage			
Farm machinery	125.5	119.0	222.0
Irrigation	108.0	115	0.0
Decomposition of cotton residues (stubble management)	75.3	75.3	75.3
Use of fertilisers	442.4	463	122.0
Transport of seed cotton from farm to gin	24.8	24.8	24.8
Total for the on-farm stage	775.5	797.1	441.1
Post-farm stage			
Seed cotton drying (LPG-powered process)	190.6	190.0	190.0
Gin machinery (electricity-powered operation)	148.0	148.0	148.0
Bale packaging	16.6	16.6	16.6
Gin trash treatment	41.8	42.9	42.9
Cotton lint rail transport to port (550 km distance)	22.2	22.2	22.2
Total for the post-farm stage	419.2	419.7	419.7
Whole life cycle			
Total life cycle emissions (cradle-to-port)	1600.6	1629.0	1183.1

Table 7Results of the sensitivity analysis—changing the fertiliser-related N₂O emission values.

LCA system-boundaries	Climate change impact of cotton lint produced in Northwest NSW (kg CO ₂ e/t lint)			
	Using the IPCC emissions values	Using the Australian emissions values	Using the Northwest NSW emissions values	Using the Queensland emissions values
Cradle-to-port	1810	1530	1564	1550
Within farm boundaries	1000	715	752	743
Fertiliser use only	690	405	442	433

This change was due to 7910 kg CO₂/ha absorbed from the air by the cotton crop and 3950 kg CO₂/ha of calculated emissions from soil associated with the decomposition of cotton residue.

3.5.5. Change to the applied inventory

The results of the sensitivity analysis related to the changing of the applied inventory data are provided in Table 9, including the potential change (in percent) of climate change impact, when the lower-end and the upper-end figures were applied.

4. Discussion

Throughout this paper, we have provided detailed analyses of key management options to achieve greenhouse gas mitigation, as was our objective. These results will provide the Australian cotton production industry with an understanding of the quantum of greenhouse gas emissions reductions that may be achieved using these strategies. As the economic and practical circumstances differ between enterprises and over time, implementation at a farm or policy level will require further analysis in the context of additional

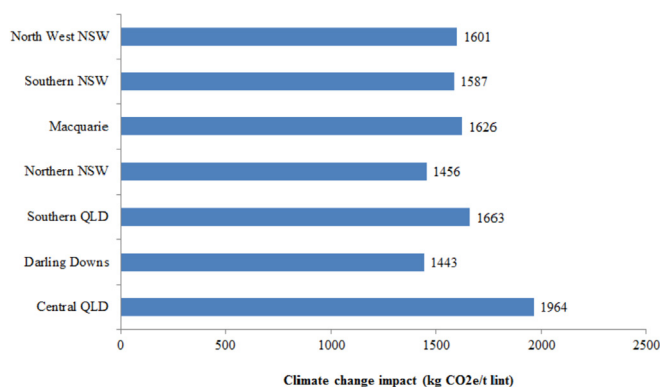


Fig. 3. Regional impacts of cotton growing on climate change impact.

variables (such as crop rotation) from a situation-specific view point which can be supported by tools, such as myBMP. It was not our intention to determine the relative benefit of each strategy to particular enterprises or growers, nor to determine whether economic and environmental objectives aligned. However, even though we present a diverse array of options, from those which are easily adopted in the short term to those which require longer-term investment, we were deliberate in our choices, excluding some approaches on the basis of their level of practicality or lack of maturity, as discussed further below. This work also has broader applicability than implementation of the specified management options in a farm, policy or market context. Given the gap in knowledge about the greenhouse gas emissions intensity associated with Australian cotton production, we extrapolated the results for northwest New South Wales to other regions and tested the sensitivity of the emissions profile to our given system assumptions.

4.1. Mitigation strategies

Of the farm-level mitigation strategies, the greatest reduction in calculated emissions intensity was achieved through reduction of the rate of N fertiliser to the economically optimum rate (13.2% GHG reduction). Whilst 180 kg N/ha is the long-term economic optimum, growers tend to apply a higher rate as a risk management strategy to ensure that yield is not compromised. A more modest emissions saving (2.6% GHG reduction) was achieved at the

biologically optimum rate of 240 kg N/ha (Macdonald et al., 2015). The economic analysis of cotton monoculture systems revealed a gross margin of AU\$ 1744/ha (Nachimuthu et al., 2017) or AU\$ 1.11/CO₂e @ 240 kg N/ha. Reducing the fertiliser rate to 180 kg N/ha resulted in gross margin of AU\$ 1795/ha or AU\$ 1.29/CO₂e, suggesting a slight improvement in combined economic and environmental performance. The emissions savings associated with a change to fertigation (i.e. reduced diesel manufacture and use during pre-plant fertiliser application) was only responsible for an emissions reduction of 2.1%. Whilst a more substantial reduction (5.9%) was calculated for the use of controlled-release and stabilised fertilisers (Tian et al., 2015), specific investigation of the economic cost/benefits of such an approach are required before adoption at an enterprise level. Also, variability in commodity and carbon prices and market access would influence the effectiveness of this strategy from a policy perspective.

So, from the perspective of fertiliser formulation, rate and method of application, the results presented here point to improved N budgeting as the preferred mitigation strategy. Adoption of this strategy may be driven by the methodology for improved fertiliser use efficiency in irrigated cotton under the Australian Emissions Reduction Fund (Australian Government, 2015b; CFI, 2011) and by ongoing development of Environmental Product Declarations, which are likely to drive maintenance and access to new commodity markets on the basis of lower emissions intensity. The Australian Emissions Reduction Fund provides growers with credits for implementing N₂O emissions reduction practices, demonstrated through the use of an Irrigated Cotton Calculator.

The use of a chickpea rotation crop provided only a modest emissions reduction (3.9%) when the yield increase brought about by the break crop was considered. However, we assumed that the N application rate for the subsequent cotton crop was not reduced, for consistency with common practice and assumed that soil carbon sequestration had reached a steady state, for consistency with the NIR. As there is an expectation under the Australian Emissions Reduction Fund that biologically fixed N provided by legume rotations can be used to offset use of synthetic N fertiliser and therefore reduce net emissions, a better understanding of the trade-off between carbon sequestration and N fixation is required. Legume crops produce a lower quantity of biomass which may offset reductions in N₂O emissions in cereal cropping (Brock et al., 2016a) and this may also be the case for legume-cotton rotations. At the same time, N fertiliser reduction may be possible without

Table 8

Key modelling parameters used to calculate the climate change impacts of cotton production in various regions.

Region	Irrigated yield (bales/ha)	Dryland yield (bales/ha)	NFUE ^a	Fertiliser applied (kg N/ha)	EF1 ^c and EF4 ^d	FracWet ^e	IWUI ^b	Irrigation water use (ML/ha)	Electricity for irrigation (kWh/ha)	Diesel for irrigation (l/ha)
Central QLD	7	Not grown	7.5	211.9	0.0037	0.71	1.51	4.6	37.0	50.3
Darling Downs	8.8	6.4	10.7	186.7	0.0033	0.71	3.15	2.8	22.5	30.6
Southern QLD	10.2	6.3	8.3	279.0	0.0105	0.71	1.52	6.7	53.9	73.2
Northern NSW	10.8	5.0	10.6	231.3	0.0045	0.93	1.77	6.1	49.0	66.7
Macquarie	11.8	1.0	9.7	276.1	0.0098	0.93	1.23	9.6	77.2	105.0
Southern NSW	10.6	Not grown	11.1	216.8	0.0039	0.93	1.13	9.4	75.6	102.8
Northwest NSW	10.5	5.0	9.34	255	0.0063	0.93	1.36	7.7	61.9	84.2

^a Nitrogen Fertiliser Use Efficiency (kg lint/kg of N fertiliser).

^b Irrigation Water Use Index (bales/ML of irrigation water).

^c kg N₂O–N (N₂O as N) is produced per kg of input synthetic N fertiliser.

^d kg N–N₂O per kg (NH₃–N + NO_x–N) volatilised.

^e Fraction of fertiliser N available for leaching and runoff.

Table 9
Results of the sensitivity analysis—change in applied inventory values.

Sensitive parameter	Sensitivity range		Applied quantity	Unit	Climate change impact of the sensitivity range (kg CO ₂ e/t lint)		% increase or decrease (–) in the climate change impact by using the sensitive range	
	From	To			From	To	From	To
Yield of irrigated cotton	8.5	14.5	10.5	bales/ha	1838	1315	14.8	–17.9
Yield of dryland cotton	2	7	5	bales/ha	1643	1576	2.6	–1.6
Gin trash content in the gin outputs (changing seed/lint ratio)	6	16	11.7	%	1538	1773	–3.9	10.7
Cottonseed price	200	500	300	\$/t	1673	1477	4.5	–7.8
Cotton lint price	400	600	474	\$/bale	1565	1646	–2.3	2.8
Irrigation water	5.5	9.5	7.7	ML/ha	1559	1639	–2.6	2.4
Fertiliser application rates	150	400	255	kg N/ha	1194	2910	–25.4	81.8
Total dynamic head of groundwater	15	105	35	m	1560	1751	–2.6	9.4
Electricity used at gin	25	45	33	kWh/bale	1566	1655	–2.2	3.4
Heat used at gin for seed cotton drying	35	75	51.3	MJ/bale	1541	1689	–3.8	5.5
Mass fraction of cotton lint in 1 kg of gin output (lint + seed + gin trash)	0.45	0.39	0.42	Fraction	1622	1581	1.3	–1.3
Mass fraction of gin trash stockpiled	0.0 ¹	1.0	0.75	Fraction	1615	1597	0.9	–0.3
Fraction of electrical energy in total irrigation energy	0.0 ²	1.0	0.15	Fraction	1599	1626	–0.1	1.6
Mass fraction of irrigated cotton in total produced cotton	0.0 ³	1.0	0.94	Fraction	1184	1629	–26.1	1.7

¹ 0.0 = 100% of gin trash as landfill; 1.0 = 100% of gin trash is stockpiled.

² 0.0 = 100% of energy is from diesel; 1.0 = 100% of energy is from mains electricity.

³ 0.0 = 100% of cotton is dryland; 1.0 = 100% of cotton is irrigated.

compromising yield. So, an improved understanding of the role of legume rotations in cotton production systems is required to avoid an undesired net increase in emissions intensity. Even though this management option requires a more substantial change at a farm-level than those associated with a change to fertiliser application rate and type, the knowledge and technology for chickpea production is readily available, and many Australian cotton growers already grow chickpea.

The use of solar-powered irrigation pumps in preference to diesel-power (Xiang et al., 2017), a practice change which is growing in momentum (Closas and Rap, 2017), provided the greatest calculated emissions savings from an energy use perspective (8.1% reduction) and the third largest saving overall. Whilst some cotton growers are early adopters of solar-powered irrigation, uncertainty about future energy and diesel prices is currently constraining further expansion (AAEP, 2016), and it is unclear as to the extent to which the Climate Change Fund will support an energy transition by growers in NSW (NSW Office of Environment and Heritage, 2017). Given the need for greater investment and forethought for this mitigation strategy, market certainty is particularly important for farmer adoption to occur.

We calculated a 3.9% saving in GHG emissions by replacing diesel-powered farm machinery with biofuel-powered machinery. As we did not account for alternative uses of the biomass or potential land use change, this calculation provides an upper estimate of the potential emissions savings. An alternative would also be the use of unblended biodiesel (B100) supplied from waste sources (e.g. recycled cooking oil), for which manufacturing emissions and potential agricultural land use change is less relevant. However, few diesel engines are warranted by manufacturers for use of blends above B5 (5% biodiesel: 95% petroleum diesel).

Three other management options we considered were: the use of organic fertilisers; the use of pressurised irrigation systems; and energy recovery from gin trash. These options were not pursued in the current study because they are more constrained from practical and/or economic perspectives. Whilst the use of organic rather than synthetic fertilisers is reported (Moritz and Kordula, 2013; Cotton Inc. and PE International A.G., 2012; Khabbaz, 2010) for some Australian cotton growing regions (e.g. Darling Downs and, more recently, Murrumbidgee and Murray Regions), the scarcity of

organic fertilisers in northwest NSW warranted its exclusion as a viable alternative from the present study (Scott, 2012; Khabbaz, 2010). Emissions savings would be partly offset by potential benefit to other crops grown in the cotton production system. The application of pressurised irrigation technologies, whilst reducing N fertiliser use by 25–50% and reducing irrigation water use by 30–50% in Syrian cotton systems (Janat, 2008), do not seem to be effective mitigation strategies for northwest NSW (Constable et al., 1990; Hodgson et al., 1990), especially when the energy requirements for these systems are taken into account (Hedayati et al., 2016). The use of gin trash for energy production for cotton ginning operations is technically possible and would reduce emissions, but commercial examples could not be found within Australia.

Other on-farm factors may lead to finer scale adjustments in the total GHG profile associated with Australian cotton production. The length of irrigation furrows impacts on water use efficiency and machinery fuel use efficiency. Also, the choice of aerial versus ground application of plant protection products would also alter the emissions profile. The adoption of new round-bale cotton pickers over older module-builder systems may increase energy efficiency as well as reducing labour costs. However, the newer round-bale pickers may increase soil compaction, resulting in an increased frequency of deep ripping which is highly energy and emissions intensive. Other adjustments to reduce compaction e.g. through alteration of tyre pressure (Antille et al., 2016) may reduce the need for deep ripping to alleviate subsoil compaction and maintain yields.

4.2. Testing new technologies: Bollgard III

The present study provides a framework from which new technologies can be tested, both those developed specifically for mitigation purposes and other new technologies that may have emissions consequences. By 2014, more than 90% of cotton growers were using Bollgard II cotton varieties (Roth, 2014), with pupae busting a mandatory requirement for pest resistance management. The soil disturbance associated with this practice, which occurs within four weeks of harvest, has emissions consequences, both through increased diesel use and potential soil carbon loss.

However, with the introduction of Bollgard III over the past two seasons, the pest resistance management strategy only requires pupae busting and soil disturbance after harvest if the first defoliation occurs after 31st March in NSW (CottonInfo, 2017). The potential reduction in tillage will assist in the preservation of soil organic matter and thus improve the soil's sustainability.

Long-term soil carbon monitoring studies in Australian cotton farming systems suggest a decline in soil organic carbon levels with both minimum and maximum tillage, with a more pronounced decline under maximum tillage (Hulugalle and Scott, 2008). However, Rochester (2011) reported the possibility of sequestering soil organic carbon under a suitable rotation crop and soil management regime. The long-term carbon sequestration potential of corn and wheat rotations in cotton farming systems are currently being tested (Hulugalle et al., 2014). As soil disturbance also leads to carbon losses in runoff and erosion (Nachimuthu and Hulugalle, 2016), future life cycle analysis should incorporate new field-level data currently being generated about carbon losses (Nachimuthu et al., 2018). Also, recent findings about the extent to which irrigation transports carbon to the field provides another dimension to be explored in future emissions mitigation studies, along with an understanding of broader implications from soil erosion (Chappell et al., 2015).

4.3. Extrapolation of the present study

We found the parameters for the present study to be relatively representative of those for other Australian cotton production regions. So, with careful consideration of interacting parameters and an understanding of system differences (e.g. dynamic head for irrigation water), it is possible to provide a meaningful extrapolation of our findings to a national scale. In addition to yield as a key determinant of emissions intensity, the extent of dryland production is also important, with dryland production found to have a calculated emissions intensity approximately 72% of that of irrigated production. A change in water availability and a trend to increased production in southern NSW may shift the proportion of dryland production in Australia over time.

Whilst a change to dryland production is unlikely to be used as a mitigation strategy, different opportunities to achieve mitigation reduction are present in dryland systems, e.g. skip-row planting. Also, levels of soil erosion and carbon loss are likely to be lower in dryland systems, with the distinction even more pronounced when pupae busting or soil disturbance requirements are considered. Whilst we accounted for lower N fertiliser requirements in dryland systems, we did not adjust emissions factors for lower soil moisture, given the small contribution of dryland cotton (4%) to overall production volumes. Further assessment in these contexts is warranted, especially given the variability in the extent of dryland production, which was 14% of total production during the 2017–18 season in northwest NSW.

5. Conclusions

The cotton industry in Australia is highly efficient and its emissions intensity is kept comparatively low by high yields, which may assist efforts to meet Australia's international obligations regarding emissions reduction. The present study demonstrated several opportunities to further reduce GHG emissions intensity (e.g. optimising N fertiliser rate, using modified fertiliser N products, using solar powered irrigation systems, using biofuel, modifying crop rotations). As the identified practice change strategies may not be currently profitable in their own right, it is critical for policy mechanisms to continue to evolve and ensure that both commodity and carbon market support continuous improvement.

The present study provides a platform which can be updated with new field-level research to explore N₂O emissions reduction and the role of soil carbon. It also provides a platform from which to continue testing practice change on GHG emissions, such as the introduction of Bollgard III. Studies such as this will lead to updating of grower-focused systems, such as myBMP, the Irrigated Cotton Calculator, and potentially widespread adoption by cotton growers.

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